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NOVEL APPROACH TO THE DETERMINATION OF MUON STICKING TO HELIUM IN THE μCF REACTIONS

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The probability ω_s of muon sticking to a helium fusion product of the muon catalyzed fusion (μCF) $d + t$ reactions in the $D_2 + T_2$ mixture

$$dt\mu \longrightarrow {}^4He\mu + n \quad (1)$$

$$dt\mu \longrightarrow {}^4He + n + \mu \quad (2)$$

determines the maximum number of the $d+t$ reactions initiated by a single muon [1] and thus it is the subject of many theoretical and experimental investigations (see review in ref. [2]). Due to the smallness of ω_s ($\cong 0.005$) the direct observation of the Heμ fusion product is rather complicate and besides it can be made now only at a low tritium concentration [3].

The main experimental data on the value of ω_s have been obtained in refs. [4], [5] by indirect method - from the analysis of the time distributions of neutrons from reactions (1), (2). These distributions have the well known form [1] :

$$dN_n/dt = \epsilon_n \cdot \lambda_c \cdot exp[-(\lambda_0 + \omega_s \cdot \lambda_c) \cdot t], \quad (3)$$

where $\lambda_0 = 0.455\,\mu s^{-1}$ is the free muon disapperance rate , λ_c is the cycling rate of the processes (1), (2) and ϵ_n is the neutron detection efficiency. The obtained results revealed some disagreement between different experimental groups and some deviation from the theory predicton.

As follows from expression (3) for the time distribution of *all* neutrons, both channels of the breaking of the fusion reactions chain are combined in one exponential factor so that they cannot be distinguished. It would be important to consider a such measuring method which allows one to select the events connected with muon sticking. The first step in this direction was undertaken by V.Zinov in ref. [8]. A few years ago he suggested to consider the distributions of the time intervals between the last detected neutron and the moment of mu-decay electron escape. In this special case the electron time distribution is the sum of two exponents with sifficiently different slopes:

$$dN_e/dt = ((\lambda_0/\lambda_n) \cdot [w \cdot \lambda_c \cdot exp(-\lambda_0 \cdot t) + \epsilon_n \cdot \lambda_c \cdot (1-w) \cdot exp(-(\lambda_0 + \lambda_n) \cdot t)], \quad (4)$$

where the value of λ_n is expressed as

$$\lambda_n = (\epsilon_n + w - \epsilon_n \cdot w) \cdot \lambda_c \quad (5)$$

The expression (4) is normalyzed to the number of muons so that its integral is equal to the yield of the first (or the same, last) detected neutrons. The ratio of the "slow" (λ_0) to fast components of it is proportional to the value of ω_s/ϵ_n that is to the sticking probability in the *observable cycle.*

Another possible way to determine the probability ω of muon sticking to helium in the μCF reaction is connected with the measurements of the yields of the successively detected (k-th) events of the fusion reaction products [6]:

$$y_k = y_1 \cdot [y_1 \cdot (1-\omega)]^{k-1} = y_{k-1} \cdot y_1 \cdot (1-\omega) \tag{6}$$

This relation can be transformed to the "differential form" for obtaining the multiplcity distribution

$$f(k) = y_{k-1} - y_k = y_1 \cdot [1 - y_1 \cdot (1-\omega)] \cdot [y_1 \cdot (1-\omega)]^{k-1}, \tag{7}$$

or to the "integral form"

$$1 - \omega = y_1{}^{-1} - y^{-1}, \tag{8}$$

where y is the total yield of the fusion reaction events. Note that as in the previous case (neutron time distributions) , one should use the value of $w = \omega_s + \cdots$ instead of ω_s to take into account small corrections due to the muon losses in the accompanying $d+d$ and $t+t$ reactions.

The remarkable feature of eqs.(6-8) is that they can be applied to the determination of ω without knowing the detection efficiency of the fusion reaction products and of the influence of possible admixtures with $Z > 1$. The formula (6) has been used in ref. [7] for the determination of the probability of muon sticking to helium in the $t+t$ fusion reaction. However, it is hardly possible to obtain on their base the reliable data for the muon sticking in reaction $d+t$ because of the smallness of the value of ω_s. It follows from the consideration of the problem that one should measure the yield of the first detected neutrons with an accuracy of 0.1% to obtain the relative accuracy 10% in the value of ω. The necessary statistics can be otained rather simply but the problem arises to prove the realibility of the data obtained. The problem is complicated due to the fact that in this method again there is no separation between the events related with "sticked" and "unsticked" muons.

Quite different situation takes place if one consideres the multiplicity distribution for each single muon in a *definite time interval* T in which muon does not decay. To satisfy this requirement one should introduce the selection criterion

$$T < t_e, \tag{9}$$

where t_e is the time interval between the muon stop and its decay. Then in the absence of sticking the multiplicity distribution has a form of Gaussian with the mean number of neutrons (the number of the observable cucles)

$$k_{max} = m = \epsilon_n \cdot \lambda_c \cdot T \tag{10}$$

If the sticking is "switched on", this distribution is distorted - an additional term arises, falling with k according to formula (7). With the selection (9) the expression for the yield of the first detected neutrons in it is described by the rather simple formula

$$y_1{}^{-1} = 1 + w/\epsilon_n - w \tag{11}$$

and it does not depend on λ_c. As value w/ϵ_n means the muon losses in the observable cycle, the relative part of the "unsticked" events in the multiplicity distrbution must be equal to $(1 - w/\epsilon_n)^m$.

Fig. 1 presents the Monte-Carlo simulated multiplicity distribution for the events from the μCF $d+t$ reaction. Events were selected according to criterion (9) where the value of T was chosen to be $T = 2\,\mu s$. The physical parameters used in the calculations correspond to the cycle rate $\lambda_c = 150\,\mu s^{-1}$, the neutron detection efficiency was put equal to $\epsilon_n = 0.4$. As seen from the figure, the reliable separation of the "unsticked" events (the gaussian peak) from the "sticked" events takes place for this distributions.

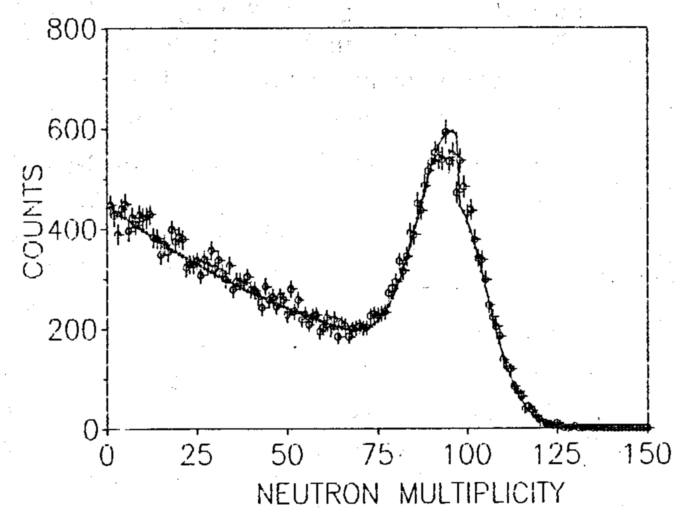

Figure 1: The simulated neutron multiplicity distribution for the observation interval $T = 2\,\mu s$. The curve corresponds to the expression (12) with an optimal parameters found from the fit.

The curve in fig. 1 corresponds to the expression

$$N(k) = N_1 \cdot [f(k) + (1 - w/\epsilon_n)^m \cdot g(k; m)], \tag{12}$$

where N_1 is the total number of the first detected neutrons in the fixed time interval T (the sum of $N(k)$), $f(k)$ is described by formula (7) with y_1 according to eq. (11) and $g(k;m)$ is Gaussian

$$g(k;m) = exp[-(m-k)^2/2\sigma^2]/[\sqrt{2\pi}\cdot\sigma] \qquad (13)$$

Optimal values of the parameters of the function (12) (N_1, w/ϵ_n, w, m and σ) were found from the fit. They are in a very good accordance with one used in the Monte-Carlo calculations. One can seen from the figure that rather good agreement takes place between the stimulated distribution and the approximation function.

It follows from our analysis that the value of w/ϵ_n can be reliably determined from the fit of the multiplicity distribution. For example, for the total statistics $N_1 = 10^5$ its accuracy is estimated to be less than 0.5%. The value of w is also among the variable parameters but the fit is rather unsensitive to it. As in the Zinov's method one must know the detection efficiency for determination of w.

We believe that the direct method of the observation of the μCF reaction events considered in the present work would be useful for the indepented determination of the muon sticking to helium fusion product. Note that this approach is most effective for the high detection eficiency of the μCF reactions. Such an opportunity is being provided by the full absorption neutron detector [9] which is employed in our experiments.

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Новый подход к определению вероятности прилипания мюона к гелию в реакциях мюонного катализа

В работе показано, что измерение множественности событий многоциклового мюонного катализа на определенном временном интервале дает возможность отделить (непосредственно наблюдать) события синтеза, прерванные из-за прилипания мюона к гелию, от событий, последовательность которых обрывается распадом мюона.

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Filchenkov V.V. E15-92-315

Novel Approach to the Determination of Muon Sticking to Helium in the μCF Reactions

In this paper it is shown that the measurements of the multiplicity of the μCF events in a definite time interval makes it possible to distinguish the fusion events interrupted because of the muon sticking to the helium nucleus from those events which are stopped due to the muon decay.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

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